

THE LAMBDA-POINT EXPERIMENT:

HELIUM CRYOSTAT, CRYO-SERVICING, FUNCTIONS, AND PERFORMANCE

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ABSTRACT

The Lambda-Point Experiment (LPE) flew on the USMP-1 (U.S. Microgravity Payload) mission on Space Shuttle Columbia. The launch occurred on October 22, 1992. The goal of the experiment was to measure the singularity in the specific heat of helium around the lambda transition at 2.177 K, with nano-Kelvin resolution. The instrument was developed by Professor J. Lips and his team at Stanford University. The flight instrument was built under a contract to Ball Aerospace in Colorado. The Jet Propulsion Laboratory (JPL) provided the cryostat facility and overall management of the experiment. The cryogenic system, functions, and performance are described in detail below. Before flight, over 100 cryo-servicing operations, covering a 20-month period from the first cool-down, were performed. The cryostat's performance in space, exceeded expectations, primarily because of the low outside-shell temperature. The temperature stability of the cryostat was maintained by passive control with a liquid/vapor phase separator,

INTRODUCTION

The Lambda-Point Experiment (LPE) flew on the STS-52 mission aboard the Space Shuttle Columbia, from October 22 to November 1, 1992. Dr. John Lips from Stanford University is the principal investigator for the experiment. The LPE measured the specific heat of liquid helium around the lambda transition (2.177 K) between normal and superfluid helium. The flight data are still being analyzed. The experiment utilized the Shuttle's microgravity environment to minimize hydrostatic broadening of the transition in order to get ultraprecise measurements. The overall flight system was assembled and tested at the Jet Propulsion Laboratory (JPL). Technical challenges in supporting the experiment are described elsewhere.²

The superfluid helium cryostat (120 L) first flew as part of the Spacelab 2 mission in 1985. For the LPE, the cryostat was modified to accommodate the flight instrument. The instrument with associated electronics was built by Ball Aerospace Systems Group in Boulder, Colorado. The experiment is sponsored by the Microgravity Science and Applications Division (MSAD) of the National Aeronautics and Space Administration (NASA). JPL has the overall management responsibility for the experiment. LPE was part of the first United States Microgravity Payload (USMP-1) mission, which was managed by the Marshall Space Flight Center (MSFC). The Shuttle integration and associated functional and mission sequence tests were performed at Kennedy Space Center (KSC). The mission was conducted from the Payload Operations Control Center (POCC) at MSFC.

The cryostat with instrument installed was cooled from room temperature and filled with liquid helium in February 1991. One year later, it was shipped cold from JPL to KSC, and it was kept cold until the tenth day of the mission. After the flight, the equipment was returned to JPL from KSC for post-flight tests and

preparation for future science experiments. The first experiment to reuse the low-temperature research facility will be the Cent'ined Helium Experiment (CHeX), scheduled for flight aboard the Shuttle in October 1996.

GENERAL CONFIGURATION

The LPE was attached to the MPES (Mission-Peculiar Experiment Support Structure). The major elements include the cryostat with the instrument probe and magnetic shield, the electronics support frame assembly, the vacuum maintenance assembly (VMA), the main electronics assembly (MEA), the power-conditioner assembly (PCA), and the shuttle acceleration monitoring system (SAMS-2). The configuration is shown in Figure 1.

The cryostat with the instrument is shown in Figure 2.

CRYO-SERVICING OF THE CRYOSTAT AND OTHER ELEMENTS

The cryostat was coded and filled with liquid helium on February 5, 1991. The calorimeter was filled with enough ultrapure ^4He that at the lambda point a vapor bubble with less than 0.1 percent of the total volume existed. The magnetic flux tubes for the high-resolution thermometers were charged to 100 gauss. All of the equipment remained at JPL for over 1 year, to February 17, 1992, when it was shipped cold with helium liquid at slightly above atmospheric pressure.

At JPL, all necessary verification tests, functional tests, vibrational tests, thermal vacuum tests, EMI tests, and soon were conducted.

The cryostat was topped off with normal helium at 4.2 K, and also at lower temperatures and pressures. Figure 3 is a general helium cryo-servicing plumbing schematic.

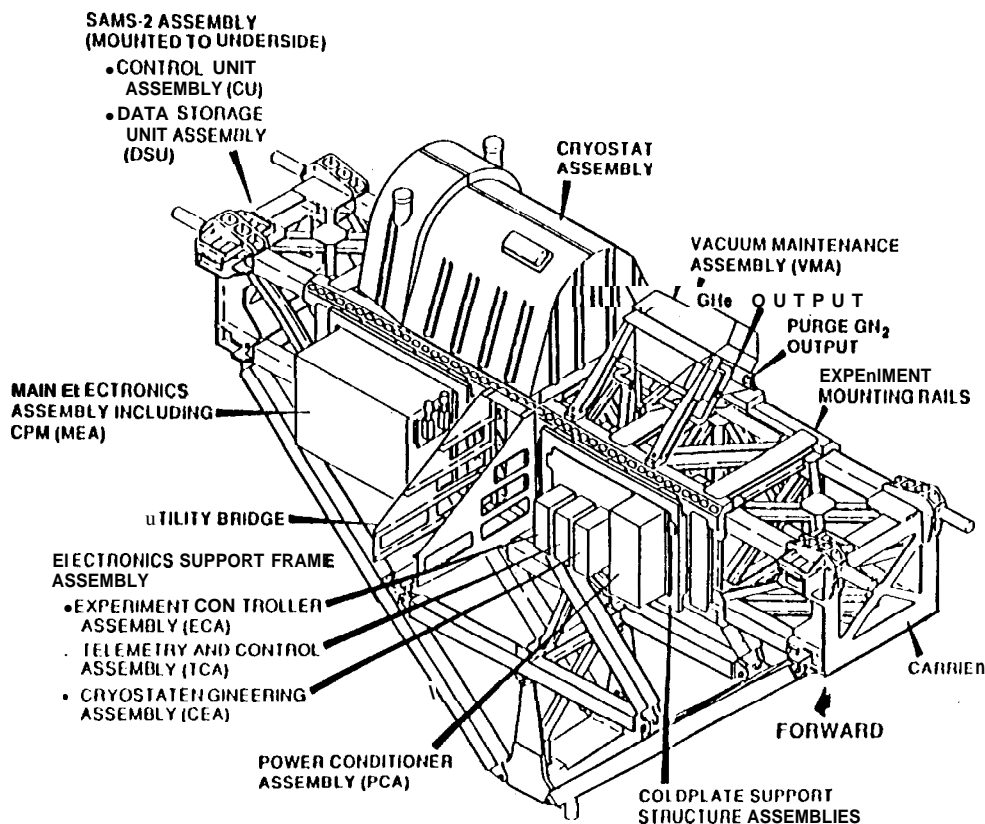


Figure 1. Air MPES payload configuration with LPE.

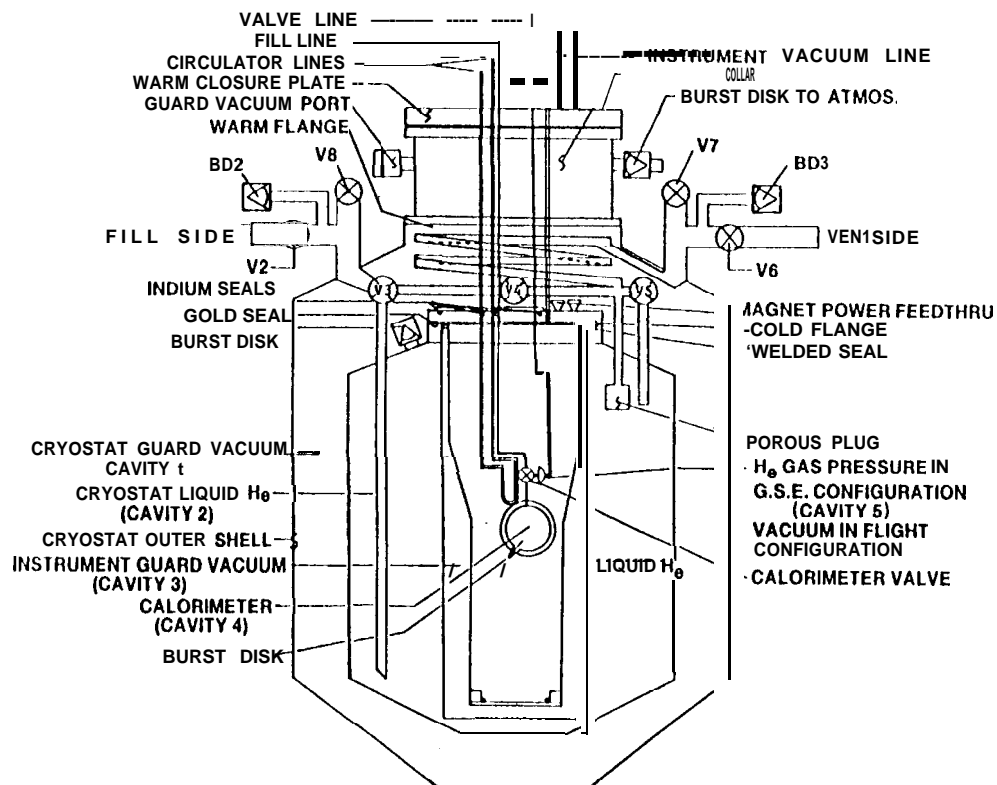


Figure 2. Cryostat cross-section with the probe installed.

At JPL, over 60 top-offs were necessary, in nearly equal numbers for normal and low-pressure top-offs. The system was transported between various testing facilities, and the actual detailed configuration had to be assembled and disassembled many times. Strict precautions and procedures were used to prevent clogging of the cryostat internal plumbing (Figure 4).

THERMAL COUPLING BETWEEN Instrument AND HELIUM BATH DURING LAUNCH

During development testing of the instrument model (in 1988), it was discovered that launch vibrational levels produced sufficient heat (~300 mW) to warm the stage 4 high-resolution thermometers. The increase in temperature was high enough that the trapped magnetic flux in the Nb tubes was lost.

The Stanford team found a solution by adding ^4He gas to the instrument guard vacuum (IGV) for the launch, and in that way thermally coupled the instrument and the bath. During system testing, it was found that ^4He evacuation out of the IGV required about 2 days. The ^4He gas fill was replaced with ^3He , and the time to reach a good vacuum in the IGV was reduced to 29 hrs. The LPE used ^3He gas for launch. The preliminary figures evaluated by the principal investigator (PI) team showed that the vacuum in the IGV was good enough for the experiment and that it was comparable to the data obtained in the lab.¹

SHIPMENT TO KSC

The whole system was shipped to KSC for integration and tests, and for the launch. The cryostat was maintained cold, either at 4 K and/or below 2 K in order to perform all necessary functional tests. The requirements at KSC were more severe with the somewhat stricter organizational structure. Many procedures used at JPL had to be expanded. LPE Team participation was essential to avoid and help to solve problems in unusual situations. The spirit and cooperation were excellent, and all challenges were met in time for successful launch and the 10-day mission.

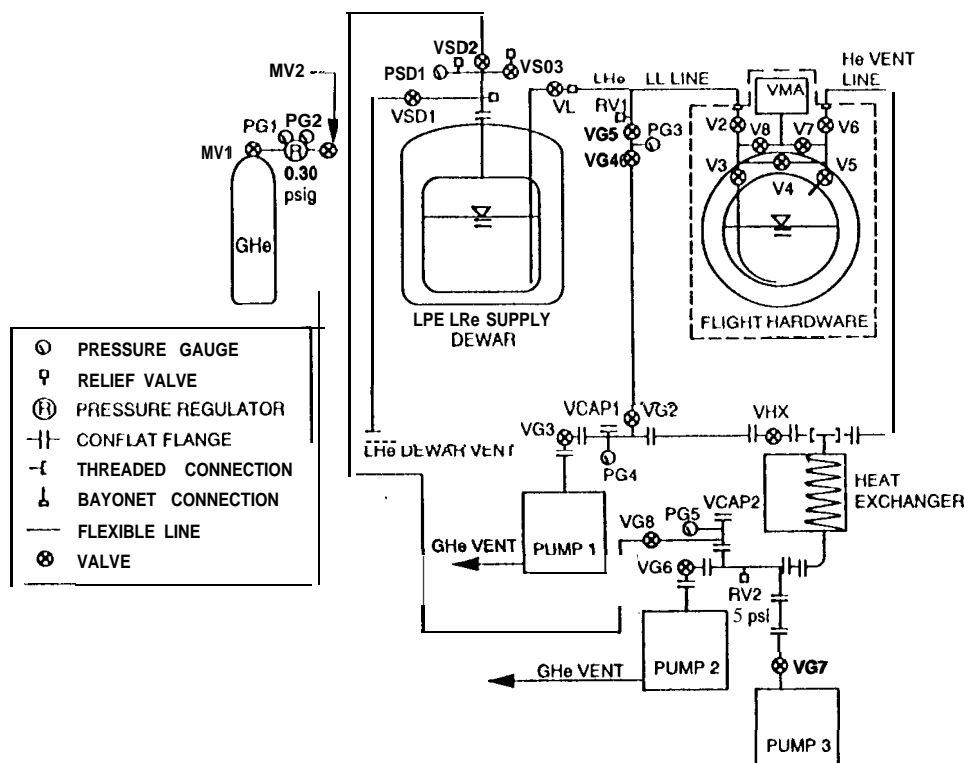


Figure 3. General helium cryo-servicing schematic.

FINAL HELIUM TOP-OFF ON THE LAUNCH PAD

The cryostat final low-pressure top-off, using a 35-ft transfer line, was successful. The final maximum volume reached 93 L at 2.3 K.

When the temperature of the cryostat reached 2 K, the volume of helium was at the 80-L level. At that point, ground support equipment (GSE) pumps were turned off and the cryostat bath isolated. Subsequently, the VMA pump was turned on, the V7 valve was opened, and the helium was maintained below T_{λ} for the fast 70 hrs before launch. Half an hour before official launch time, the VMA pump was turned off. There was a launch delay of about 2.5 hrs, but it was possible to monitor the cryostat pressure. The pressure did not reach lambda point before launch.

CRYOSTAT TEMPERATURE DURING THE MISSION

The temperature of the cryostat helium bath during flight is presented in Figure 5. About 3 hrs after launch, the experiment was turned on by the crew. The temperature was slightly below 2 K. Parallel vent valve VV2 was commanded open. The rise in the temperature to 2.05 K was owing to the activation of the 3-W heater, the closure of the largest orifice vent valve (VV3) in the VMA, and also to the activation of the adsorption pump heater.

The IGV was evacuated to space with the adsorption pump heater activated via two commendable vent valves. After 4 hours the heater was turned off, the vent valves were closed, and the adsorption pump cooled down, initialing final IGV gas pump-out. The temperature slowly dropped to between 2.05 K and 1.95 K between 7 and 22 hrs of flight. The only venting was through the smallest orifice—a noncommandable valve in the VMA.

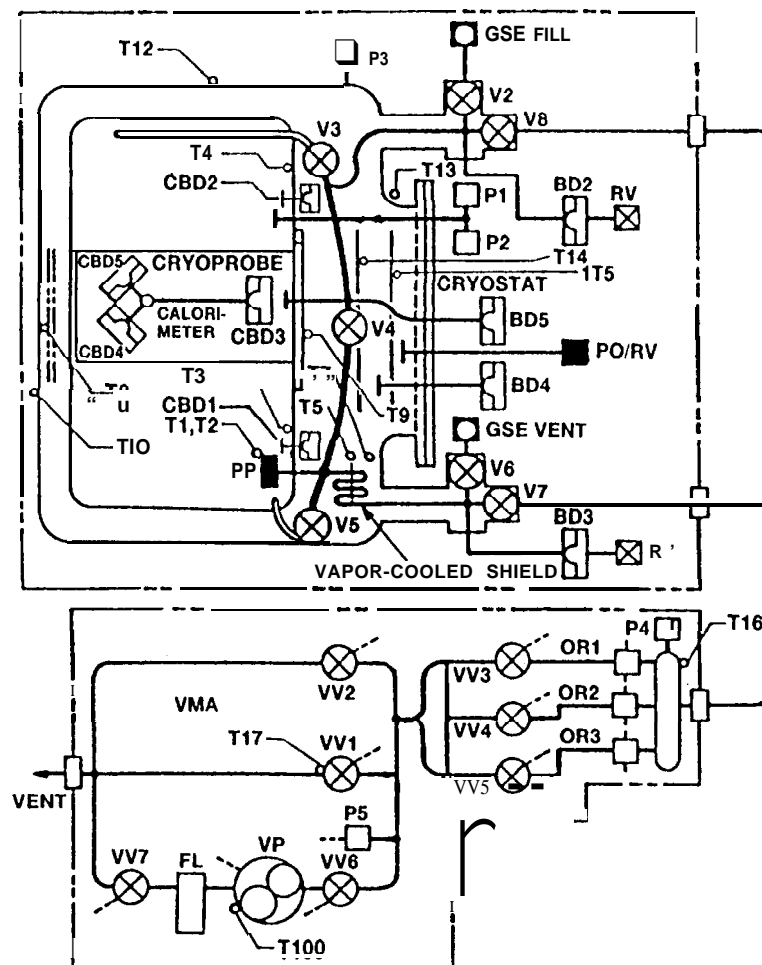


Figure 4.1. IPE cryostat plumbing schematic.

Between 22 and 23 hrs into the mission, the cryostat heater was activated twice. It was activated the first time for about 15 minutes, and the second time for about 7 minutes. This heating of the bath was needed to increase the "clearing" of the IGV volume of any residual He film and adsorbed gas. Calculations showed that the bath equilibrium should be 2.05 K. In reality, it was lower; that is why the heater was turned on to warm the bath up. The temperature reached was about 2.06 K, which was the maximum temperature allowed by the calorimeter internal thermal stage's control. At 31 hrs, the largest orifice's helium vent path was opened. In 10 hrs, the temperature stabilized at around 1.77 K, within a 10-mK range. The general acquisition of science data started about 2 days into the mission and continued until the end of the ninth day of the mission.

The temperature curve of the cryostat shows 2 additional peaks. The small temperature excursion is at ~125 hrs into the mission, and is owing to the single helium-mass-gauging sequence. The 3-W heater was activated for 68 s, just a few minutes before the Shuttle assumed the gravity gradient orientation. The cryostat temperature dropped by about 20 mK, as well. At -188 hrs of mission elapsed time (MET), the Shuttle lowered its orbit with the orbital maneuvers system (OMS). The maximum acceleration imposed on the system was of the order of at least 20 g . The helium in the cryostat was redistributed, which had an impact on the cryostat temperature control.

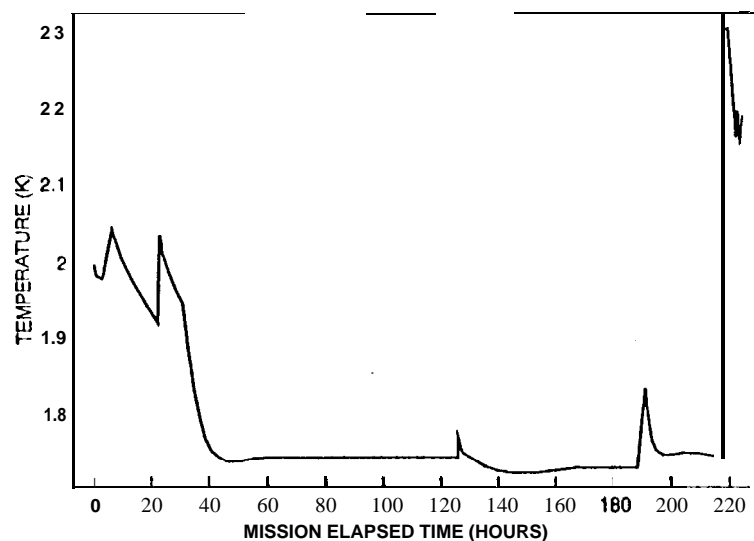


Figure 5. The cryostat helium temperature during the mission.

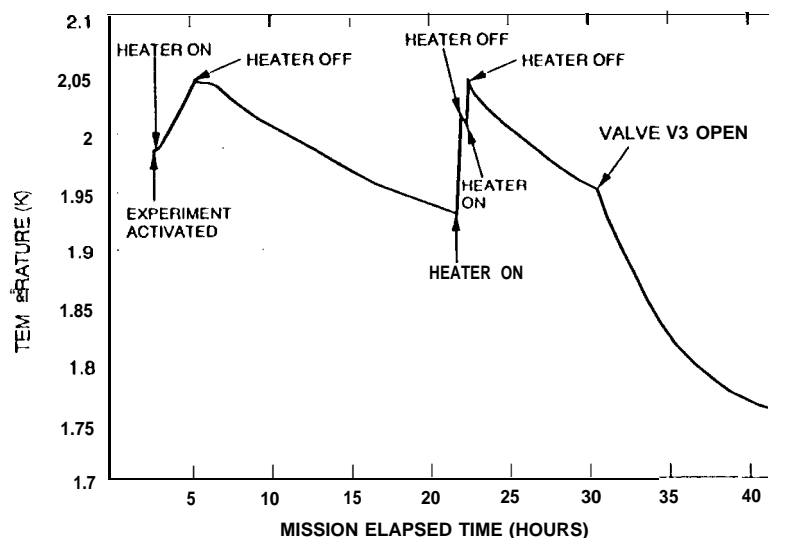


Figure 6. Temperature of the helium bath during the first 2 days of the mission.

Till; PERFORMANCE OF THE SUPERFLUID HELIUM LIQUID/VAPOR SEPARATOR (POROUS PLUG)

The LPE cryostat superfluid helium separator performed its function throughout the mission. The porous plug was of the same stainless sintered metal as that used on the Infrared Astronomical Satellite (IRAS).³ The plug dimensions are (1) diameter, 3.17 cm; (2) thickness, 1.65 cm, and (2) average pore size, 3.9 μ m.

The cryostat was launched with the porous plug positioned in helium vapor. All the vent valves were closed. Vent valve VV1 was opened during the first 2 minutes of accelerated ascent when the pressure in the Shuttle bay dropped below 650 ± 30 Pa. The opening was activated by the baroswitch and ascent power. After 3 hrs in flight, additional parallel, vent valve VV2 was opened and large-orifice valve VV3 was closed and

remained closed for 31 hrs. During the 31 initial flight hours, the cryostat temperature was between 2.05 K and 1.95 K and the temperature difference across the plug was -50 mK, with the downstream side being colder (Fig. 7). The temperature of the cryostat never stabilized during this time (Figure 6). After 31 hrs in flight, the valve with the largest orifice, VV3, was opened, and within 12 hrs the temperatures on the upstream and downstream of the plug stabilized. The temperature difference across the plug increased to $\Delta T_{pp} \approx 200$ mK. These data confirmed that the porous plug was completely dry downstream. Their corresponding fountain effect pressure difference ($\Delta p_f = \rho S \Delta T_{pp}$) is at least 10 times bigger than the normal mechanical pressure difference (~ 1300 Pa),

There were 2 perturbations on the cryostat temperature: one, at 125 hrs, was owing to the heat pulse mass-gauging. The second perturbation was caused by the OMS when the Shuttle decelerated to reach a lower orbit. The cryostat temperature slowly increased by about 100 mK, before dropping back to nearly the same level within 6 hrs. The temperature difference across the porous plug decreased to -60 mK before increasing again.

The explanation of this behavior is that the Shuttle deceleration displaced helium liquid away from the plug. The supply of helium to the plug diminished and so did the mass flow through the plug. Reestablishment of the sufficient supply was started after a few hours of the OMS firing events. It is surprising that reestablishment of the helium distribution in the tank took so long. In the lower orbit, the spacecraft could maintain and/or add small continuous deceleration, which added to the forces acting against surface tension forces. This was observed for the first time in microgravity. It has potential impact on the temperature stability of the satellites using superfluid helium if they do undergo sizable reorientations during their missions.

After 217 hrs of the mission, the remaining liquid helium was evaporated by using a 3-W heater.

Reversal of the temperature difference across the plug was used as one of the main indications that liquid helium was depleted. Subsequently, the vent valves VV 1 and VV2 were closed. The cryostat started to warm up, as well as the calorimeter.

EXTENDED ON-ORBIT LIFETIME OF LPE CRYOSTAT HELIUM

The total lifetime of the helium in the LPE cryostat was measured to be 12 days, 2 hrs. This included 2 days, 22 hrs of ground hold time and 9 days, 4 hrs on-orbit time. The parasitic evaporation rate of helium at 2 K in the LPE cryostat on the ground has been well documented to be 7.5 L/day. Noting that the quantity of helium at 2 K following the last top-off was 80 L, one can easily calculate that the quantity of helium remaining in the LPE cryostat at launch was 58.1 L. This translates into a parasitic boil-off rate on-orbit of 6.3 L/day, a 16-percent improvement over the ground rate. An explanation of the on-orbit performance improvement is presented below.

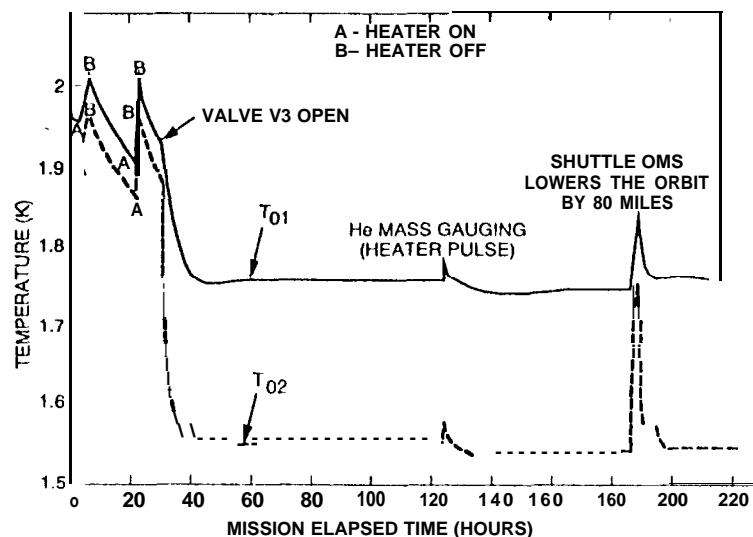


Figure 7. Temperature of the porous plug: T_{01} = inside the cryostat, T_{02} = outside.

All of the ground hold data were taken with the cryostat outer shell maintained at room temperature (-300 K). Engineering data taken from the experiment during the mission indicated outer-shell temperatures significantly lower than 300 K. The cooling of the outer shell can significantly reduce the parasitic heat leak and improve the overall performance of the cryostat.

As part of an early Low Temperature Research Facility design team activity (the team looked at future low-temperature physics flight missions) a thermal model of the LPE cryostat with the instrument insert was built. Using parasitic heat load data as a function of outer-shell temperature according to the model, and assuming a linear relationship between parasitic heat loss and outer-shell temperature (a similar result was found by Bhandari et al., 4), a relationship between the ratio of heat leak with a cooler-than-room-temperature outer shell is evaluated to be

$$\frac{Q(T)}{Q_{300}} = 0.0077T[K] - 1.277 \quad (1)$$

The assumption of the linear relationship implies that the dewar parasitics are dominated by radiation and that $Q_{\text{parasitic}} \propto T^4$ (radiation $\propto T^4$). The following equation can be used to determine the lifetime of the helium in the LPE cryostat:

$$m_{\text{initial}} h_{fg} = \int_{t=0}^{t=t_{\text{final}}} Q_{300} \frac{Q(T_{\text{shell}}(t))}{Q_{300}} dt \quad (2)$$

Here h_{fg} is the enthalpy of vaporization; m_{initial} is the initial mass of helium in the cryostat at time $t=0$; $T_{\text{shell}}(t)$ is the outer-shell temperature as a function of time, and t_{final} is the lifetime. Performing the integral and solving for lifetime results in a calculated lifetime of 12 days, 10 hrs, and 54 minutes. This calculated lifetime is within 3.3 percent of the value observed from the experiment.

The results of this analysis indicate that the parasitic heat leak for the LPE cryostat is dominated by radiation and that significant improvement in cryogen lifetime can be achieved with small changes in the outer-shell temperature for the LPE dewar. If cryogen lifetime is a concern for the next experiment on which this dewar will be used, one potential solution would be to add either passive or active cooling to the outer shell, where the LPE showed significant gains.

CONCLUSIONS

The superfluid cryostat satisfied all the requirements for the mission. The LPE succeeded in getting more data than were anticipated. The cryo-system was very reliable for over 20 months, and it was returned back to JPL in great shape, which was verified by the post-flight test.

ACKNOWLEDGMENT

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